

Fertilizer Research and Education Program

FINAL REPORT

A. Project Information

Project: 12-0385-SA

Title: Characterizing N Fertilizer Requirements of Crops Following Alfalfa

Report: Final

Time Period: January 1, 2013 - December 31, 2015

Project Leaders:

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B. Objectives

Our objective was to determine the impacts of rotation with alfalfa on the N fertilization needs of wheat, to develop an ‘N credit’ recommendation for management of N fertilizers in non-legumes rotated with alfalfa. Since wheat is a highly-responsive crop to N fertilizers, wheat was treated as a ‘bioassay’ and estimates were made on wheat that could be extrapolated to other crops.

C. Abstract

Alfalfa is a high-yielding leguminous perennial crop grown in large acreage in California, which fixes significant amounts of atmospheric nitrogen in association with N-fixing bacteria which are present in symbiosis on the plant roots. Alfalfa may ‘fix’ from 350 to nearly 1,000 lbs of N per year, and portion of this N benefits succeeding non-legume crops grown in rotation after the crop is plowed down. This residual nitrogen reduces the fertilizer N requirement of fertilizer-requiring crops such as corn, wheat, tomato, and cotton by an amount sometimes called the “legume N credit”. This project was conducted from approximately 2011 through 2015 at 3 locations as an effort to characterize the nitrogen benefit that accrues to a subsequent crop in rotation after many years of alfalfa production. We conducted replicated plot experiments at three field station sites in California using wheat as an indicator crop to assess alfalfa’s N contribution to a crop in rotation. The experimental design was a Randomized Complete Block Design with a Split Plot restriction, with cropping system as the main plots and N rates of the wheat rotation crop as subplots. These experiments were then repeated in a second set of replications (2 separate ‘year’ measurements at each site,

but each year replication took about 1.5 years). The experiment was begun before funding was secured in 2013 (starting in about 2011) – we established blocks of alfalfa at the three sites that could then be used in rotation studies. After at least two years of alfalfa growth, the ‘grain control’ blocks were established 1.5 years before the implementation of the rotation study. Then, unfertilized wheat was planted followed by sudangrass planted in the summer so that any remaining residual N was extracted before the experiment began. The experiments began when wheat was grown on either plowed-under alfalfa (alfalfa-grain) or plowed-under grain (grain-grain) rotations with N application rates ranging from 0 to 250 lb N ac⁻¹. The objective was to see the N response after (1) continuous alfalfa or (2) grain-wheat rotations. Fertilizers were applied in two stages, the first 50 lbs. at planting, following by a single application at tillering at various rates to ascertain the contribution from the previous alfalfa crop. Wheat grown without N fertilizer had more dry matter and N uptake (soft dough stage) and higher grain yields and protein content in all cases when following alfalfa. We estimate the legume N credit at the three sites to range from approximately 70 to 130 lb. N ac⁻¹, which was higher than previous estimates in California of 40-80 lb. N ac⁻¹. We also found that grain protein was benefitted at most N rates, including some of the highest rates. This benefit to wheat grain protein was important since much of the impetus for N fertilizer applications originates from the incentives for high grain protein in wheat. Additionally, it was clear that there were at some locations, rotation effects that were not apparently (or immediately) accredited to the N credit but could be due to other rotation effects such as better soil structure or breaking of disease cycles. These results have been presented in a number of field days over the 3 year project, at Tulelake, Kearney, Davis, and El Centro, and presented at the Plant & Soil Conference in Visalia, and summarized at the Western Alfalfa & Forage Symposium in Reno December.

Implications. This trial has been successful in identifying the N credits in non-legumes following alfalfa, and the first systematic experimentally-determined estimate developed for California, to our knowledge. Although quantitative results differed by soil type and location, we found benefits to rotation at all locations in all years. If these credits are considered in adjusting recommendations for N fertilizer applications for wheat (or other non-legumes) following alfalfa, millions of tons of fertilizer applications could be saved in California. For example, if a modest 80 lbs N/acre credit (in the mid-range found in these trials) is provided to the crops following the estimated 150,000 acres of alfalfa rotated each year in the state, 12 million lbs. of actual N in applied fertilizer could be conserved, with a benefit to the farmer and the environment. A few caveats should be considered here when making recommendations on the N benefits of crop rotation with alfalfa. These trials were conducted under controlled conditions, with good stands of alfalfa plowed under and compared with grain-grain cropping systems. On farms, the status of alfalfa fields varies widely in plant density and weed intrusion by the time the fields are plowed under for rotation. Additionally, soil types vary widely in the ability to conserve residual N. The time elapsing between the vigorous growth of an alfalfa field and the subsequent crop may also vary widely, and these trials were planted shortly after crop plow-down. Therefore adjustments to estimated N benefits must be made based upon a range of circumstances and modified accordingly. However, this research has quantified the N benefits to a subsequent grain crops and has implications

for N recommendations of non-legumes. Crop rotations with alfalfa occur frequently in California, and can have major environmental benefits to the state's management of nitrogen. Crop rotations with other legumes (such as cowpea, fieldbean and cover crops such as vetch) are less common, but also provide legume benefits to subsequent crops.

D. Introduction

While many growers utilize the 'recipe' approach to fertilizer applications, there are both economic and environmental incentives to more carefully calculate requirements under different soil conditions, especially for mineral N. Economic penalties for growers are incurred when imprecise estimates are used, either through yield losses from inadequate fertilization, or from excess applications which are costly. Environmental concerns from excess applications include possible effects on groundwater with N fertilizers and manure used on agronomic crops (see Harter et al. report, March, 2012, see <http://groundwater.ucdavis.edu/>) and impacts on air quality. Large impacts on groundwater contamination from N fertilizers are reported, particularly for the Tulare basin where corn, grains, and alfalfa are a predominant component of the landscape. An important strategy to better manage N for non-legumes, it is necessary to understand crop rotation effects from legumes which provide some quantity of N to subsequent crops. Data on this issue is available from other (lower-yielding non-irrigated) regions, and 'N credits' for better fertilizer management have been calculated, but to our knowledge no data has been available on this issue for California's highly productive irrigated field crops.

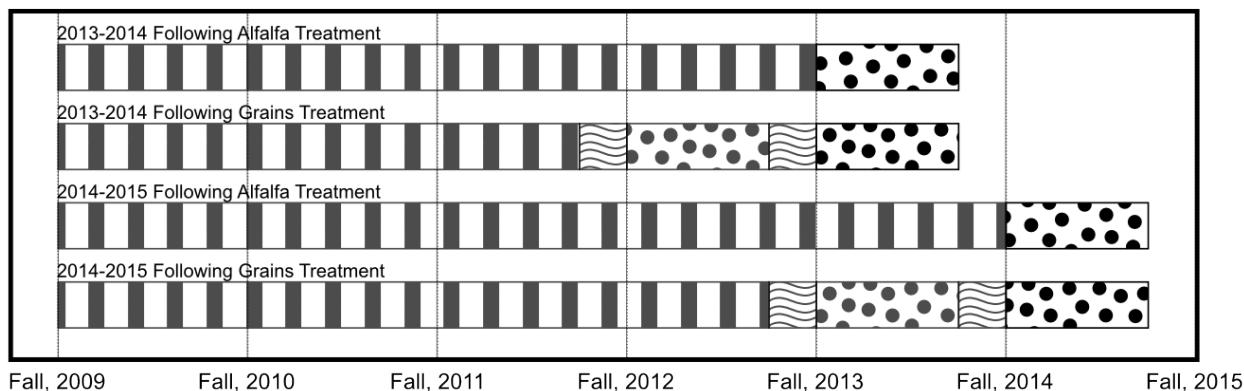
Alfalfa in California is commonly rotated with wheat, corn, oats, processing tomato, cotton, and sometimes specialty vegetables. A minimum of 200,000 acres are likely rotated from alfalfa each year in California. Alfalfa is typically in place from 3 to 6 years, and almost always followed by a non-legume. Farmers value both the soil tilth benefits of crop rotations with alfalfa, as well as the weed suppression and N benefits. However, little is known about the impacts on the fertilizer N needs of subsequent crops in this rotation, and many growers do not take this into consideration when developing a fertilizer program. Under irrigation, a productive alfalfa crop fixes between 350 and nearly 1,000 lbs. of N per acre per year in California, totaling ~ 2,000 to 4,000 lbs N/acre over a 5 year alfalfa stand. While this N is presumably removed in the forage (most of it is), some quantity of residual nitrogen remains in the soil, a portion of which may be available to subsequent crops. This is due to the stable soil rhizosphere, the sloughing off of root and nodule pieces, high quantities of soil microorganisms in a stable leguminous perennial system, the root mass itself, and the deposition of high N-containing foliage to the soil. While there have been many studies conducted in the Midwest to quantify an 'N credit' for corn or grains following alfalfa, to our knowledge there have been no studies in California to characterize this rotational N benefit under irrigated conditions. Factors such as higher temperatures, the higher alfalfa and grain yields, soil type, as well as the presence of irrigation water create conditions in California which are likely to be highly distinct from Midwestern production systems. Additionally, the wide variety of conditions (from desert to Mediterranean and mountain conditions) within California creates challenges to develop a unified recommendation for

an ‘N credit’ for crop rotations.

Our approach to this was to establish comparative cropping systems at three sites in California which represent several of the major alfalfa growing regions in the state. This compared a grain-grain rotation (of approximately 1.5 to two years without N fertilization), with an alfalfa-grain rotation (of greater than 3 years in alfalfa). After these cropping systems were established (beginning before funding was available), we plowed-down the two systems and planted wheat over the entire area, and 6 levels of N fertilization were applied as a ‘bioassay’ of the value of the residual N available to a subsequent wheat crop. Both forage yields and grain yields were obtained and N analysis of plant tissue and grain was conducted. Differences between +alfalfa and – alfalfa in rotation was determined to be the N credit value of the crop rotation.

E. Work Description

Task 1. Preparation of Experimental designs and logistics (Completed in first year). Experimental designs and logistical planning were completed, many largely before funding was secured, since long-term rotations had to be established. (see figure)



Task 2. Establishment and Maintenance of Field Plots (completed in first year) were completed at Davis, Kearney, and Tulelake. At Tulelake and Kearney we were able to establish split-plot trials due to the availability of long-term alfalfa plots there – at Davis, these are separate neighboring fields. Due to the limited funding, no plots were established at El Centro. Plots were maintained from 2013 through 2015. See Figure 1.

Task 3. 2013 Estimation of N₂ fixation utilizing the natural abundance method (N¹⁵) for Phase I. This task was eliminated upon discussions with colleagues about the value of N¹⁵ vs. the value of N uptake data.

Task 4. 2013 Plow-down, soil preparation, Phase I. (Completed in year 1-2). At each of the three locations, sudangrass and alfalfa crops were harvested for the last time and plowed down in October/November, 2013. Standard tillage techniques were used to prepare the soil for establishment of wheat.

Task 5. 2013 Soil Sampling, Phase I. (Completed year 1). After plow-down of alfalfa and sudangrass plots, soil samples were taken from each plot to characterize soil

texture, soil nutrient availability, and soil chemical properties. Soil samples were also taken from each plot by depth to 120 cm to characterize total N content. Data were summarized.

Task 6. 2013 Establishment of wheat N test plots, Phase I. (Completed year 1). Shortly after soil samples were taken from the plowed-down alfalfa and sudangrass plots, wheat was established in each plot at the three locations. Each plot was split into six subplots for establishment of wheat N treatments, which included six N rates ranging from 0 to 250 lbs N/acre in 50 lbs N/acre increments. Except for the unfertilized controls, N treatments were applied as urea: 50 lbs N/acre were applied at planting (October-November, 2013) and the remainder when the wheat was tillering (February-April, 2014).

Task 7. 2013 Establishment of Field Plots for Phase II. (Completed year 2). Phase II was essentially a replication over year to provide a total of 2 replications per site or 6 replications over site/years. Field plots were established at Davis, Kearney, and Tulelake. All three sites have split-plot trials for Phase II. Plots were not established at El Centro due to limited funding.

Task 8. 2014 Harvest and Plant Sampling, Phase I. (Completed year 2). At Davis and Tulelake, wheat plots supplied with 50 lbs N/acre and those with 250 lbs N/acre were sampled approximately once every two weeks between the jointing stage and the soft dough stage (March-April, 2014 at Davis; May-June, 2014 at Tulelake). At Kearney, wheat plots supplied with the same selected N treatments were sampled approximately once every two weeks between the boot stage and the soft dough stage (March-April, 2014). Yields were measured at the soft dough stage from areas ranging between 60 ft² and 200 ft², depending on location. Harvests for grain yield have been completed at Davis and Kearney (June, 2014), and will be completed at Tulelake soon.

Task 9. 2014 Estimation of N2 fixation utilizing the natural abundance method (N15) for Phase II. (eliminated).

Tasks 10. 2014 Plow-down, soil preparation, Phase II. (Completed year 2). At each of the three locations, sudangrass and alfalfa crops were harvested for the last time and plowed down in October/November, 2014. Standard tillage techniques were used to prepare the soil for establishment of wheat (Phase II).

Task 11. 2014 Soil Sampling, Phase II. (Completed year 2). Soil samples were taken from each plot to 120 cm to characterize residual soil N content. Soil samples were collected in October 2014 at Tulelake and in November 2014 at Davis and Kearney.

Task 12. 2014 Establishment of wheat N test plots, Phase II. (Completed year 3). Wheat was planted in test plots at all three locations in October/November, 2014. N fertilizer in the form of urea was applied at 50 lb N/acre at planting for all treatments besides the control and incorporated into the soil promptly. Application of remainder of the N fertilizer for each test plot is in progress.

Task 13. 2015 Harvest and Plant Sampling, Phase II. (Completed year 3). Wheat was harvested utilizing test-plot harvesters (biomass yields) and using grain combines for grain yields. Yields were adjusted for dry matter utilizing sub-samples.

Task 14. Laboratory Analysis (2013-2014-2015). (Completed 2015). Soil samples from Phase I were taken from 5 depths and were analyzed at the UC Davis Stable Isotope Facility for total N concentration and $\delta^{15}\text{N}$ values in April, 2014. Soil samples taken for soil characterization were submitted to the UC Davis Analytical Lab in February, 2014. Near-infrared spectroscopy (NIRS) was used to estimate total N content in Phase I plant samples. Soil samples from Phase II for characterization of residual N have been completed.

Task 15. Data Analysis and Data Summary (2014-15). (Completed year 3). Data from Phase I and Phase II have been used to create nitrogen response curves and have been statistically analyzed for differences between treatments.

Task 16. Outreach. (Completed-outreach activities in all 3 years) Field days was held in May each year at Davis in 2013, 2014 and 2015 where this rotation study was presented to farmers. Approximately 110 attending each year. This N Rotation study has also been presented at field days held on August 1, 2013; September 5, 2013; April 17, 2014; May 7, 2014; August 13, 2014; September 12, 2014. The study was also presented at the California Alfalfa, Forage, and Grain Symposium on December 11, 2014, and December 4, 2015. The data were also presented at the Plant & Soil conference in February, 2016.

(Sorghum \times drummondii) - wheat (*Triticum aestivum*) rotation (Following Grains).



Figure 1. Continuous alfalfa and grain rotation treatments at Davis in 2014.
‘Following Alfalfa’ main plots are shown next to the ‘following Grains’ plots in a split plot design, with ‘cropping system’ as main plot, and N rates as sub-plots.

F. Data/Results

Aboveground Biomass

At 0 kg N ha⁻¹, wheat aboveground biomass for the 'Following Alfalfa' treatment were higher than those for the 'Following Grains' treatment at all locations. Aboveground biomass for all locations was also lower for wheat following grain than for wheat following alfalfa for N rates up to 112 kg N ha⁻¹ (Figure 2).

At Davis, wheat aboveground biomass for the wheat following alfalfa was not distinguishably different between different levels of fertilization for the first period of the experiment, and was mostly around 15 Mg ha⁻¹. The same trend, or lack thereof, was observed for the second period of the experiment, though more variability was present between treatments. Still, the aboveground biomass for wheat following alfalfa in the 2014–2015 period was also around 15 to 18 Mg ha⁻¹. In contrast, wheat following grains appeared to produce more biomass with supplemental N, starting at 9 Mg ha⁻¹ and increasing to 15 Mg ha⁻¹ in the 2013–2014 period with supplementation ($p < 0.0001$). In the 2014–2015 period, wheat following grains at Davis yielded up to 18 Mg ha⁻¹ with N supplementation.

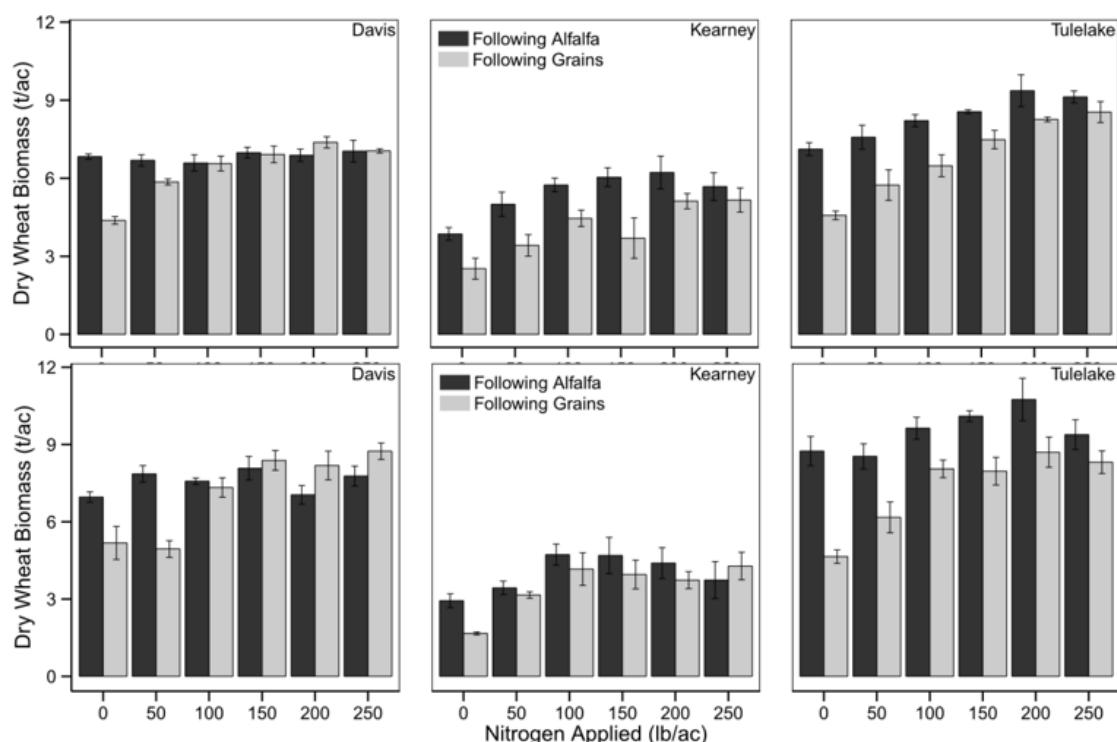


Figure 2. Dry wheat aboveground biomass following alfalfa and following grain at six nitrogen rates ranging from 0 to 280 kg N ha⁻¹ at Davis, Kearney, and Tulelake. Top: Results from 2013–2014 trial. Bottom: Results from 2014–2015 trial. Error bars represent standard errors of the mean. Light gray bars represent biomass of wheat grown after a sudangrass/wheat rotation lasting at least 1.5 years ('Following Grains'). Dark gray bars represent biomass of wheat grown after alfalfa ('Following Alfalfa').

Wheat aboveground biomass following alfalfa at Kearney and Tulelake did not follow the same trend as that at Davis. Increased aboveground biomass was seen with increasing amounts of N supplementation for both the 2013–2014 and 2014–2015 periods at Kearney and Tulelake ($p < 0.05$). However, there was no distinguishable difference between responses to fertilization in wheat following alfalfa and in wheat following the grain rotation in either year at Tulelake ($p = 0.1052$ in 2013-2014 and $p= 0.1437$ in 2014-2015). Despite the two sites having the same wheat variety, aboveground biomass at Kearney was also much lower than aboveground biomass at Davis for all N rate treatments for both experimental phases, though the maximum aboveground biomass measured for the 2013–2014 experiment was similar to that at Davis. In contrast, aboveground biomass at Tulelake was much higher than that at either Davis or Kearney.

Additionally, at Kearney for the 2014–2015 experimental period, wheat aboveground biomass was not distinguishably different between rotation treatments ($p = 0.065$), nor was it distinguishably different between nitrogen rates above 56 kg N ha^{-1} ($p < 0.05$). However, as with the wheat following grains at Davis, wheat following grains at Kearney and Tulelake also responded to N fertilization. Wheat aboveground biomass for all location-years appeared to reach the same maximum in both treatments. Additionally, lodging was observed at Tulelake in the highest N fertilization treatments for wheat following alfalfa.

Nitrogen Uptake

Nitrogen uptake in the wheat aboveground biomass mostly followed the same trends as the wheat aboveground biomass itself (Figure 3). However, the wheat following alfalfa at Davis continued to assimilate additional nitrogen, up to at least the 56 kg N ha^{-1} level in 2014–2015 and up to at least 112 kg N ha^{-1} in 2013–2014, despite the lack of a response in the biomass. Wheat following alfalfa at Davis also plateaued at the same level as the wheat following grains. Similar results were observed both years.

Like wheat aboveground biomass at Kearney, wheat nitrogen uptake at Kearney was very different for both years, with a maximum of 250 kg N ha^{-1} in 2013–2014, and a maximum of 125 kg N ha^{-1} in 2014–2015. However, in both cases, the wheat following grains reached the same maximum nitrogen uptake level as wheat following grain.

Similar to Davis, maximum nitrogen uptake levels at Tulelake were higher in 2013–2014 than in 2014–2015, but in both years, the wheat following alfalfa and wheat following grains both assimilated the same maximum amount of nitrogen at the highest level of nitrogen fertilization (280 kg N ha^{-1}).

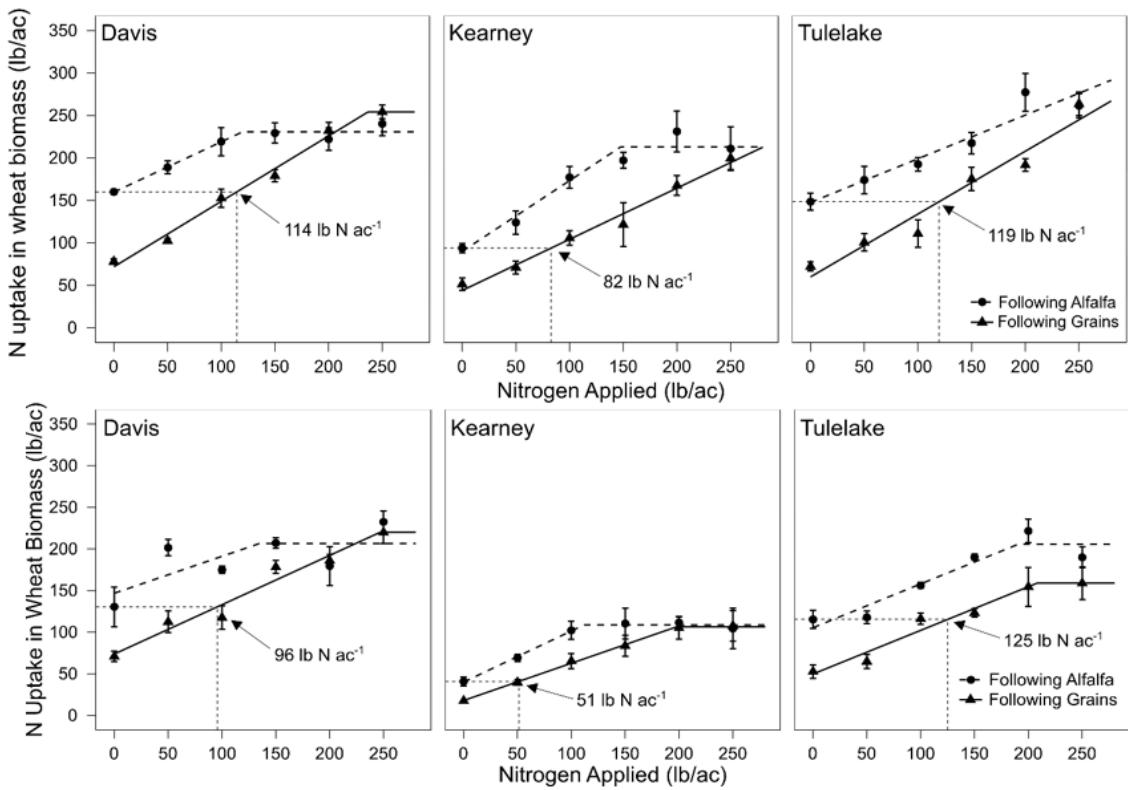


Figure 3. Nitrogen uptake in dry wheat biomass following alfalfa and following grain at six nitrogen rates ranging from 0 to 280 kg N ha⁻¹. Top: Results from 2013–2014. Bottom: Results from 2014–2015. Dashed lines and solid lines are linear-plateau regression curves for the ‘Following Alfalfa’ and ‘Following Grains’ treatments, respectively. Error bars represent standard errors of the mean. Dotted lines indicate where N uptake for unfertilized wheat grown after alfalfa was the same as N uptake for wheat in the ‘Following Grains’ treatment based on the regression curve. Numbers indicated by arrows show the quantity of N fertilizer required in the ‘Following Grains’ treatment to yield the same amount of N uptake as the unfertilized wheat in the ‘Following Alfalfa’ treatment.

Grain Yield

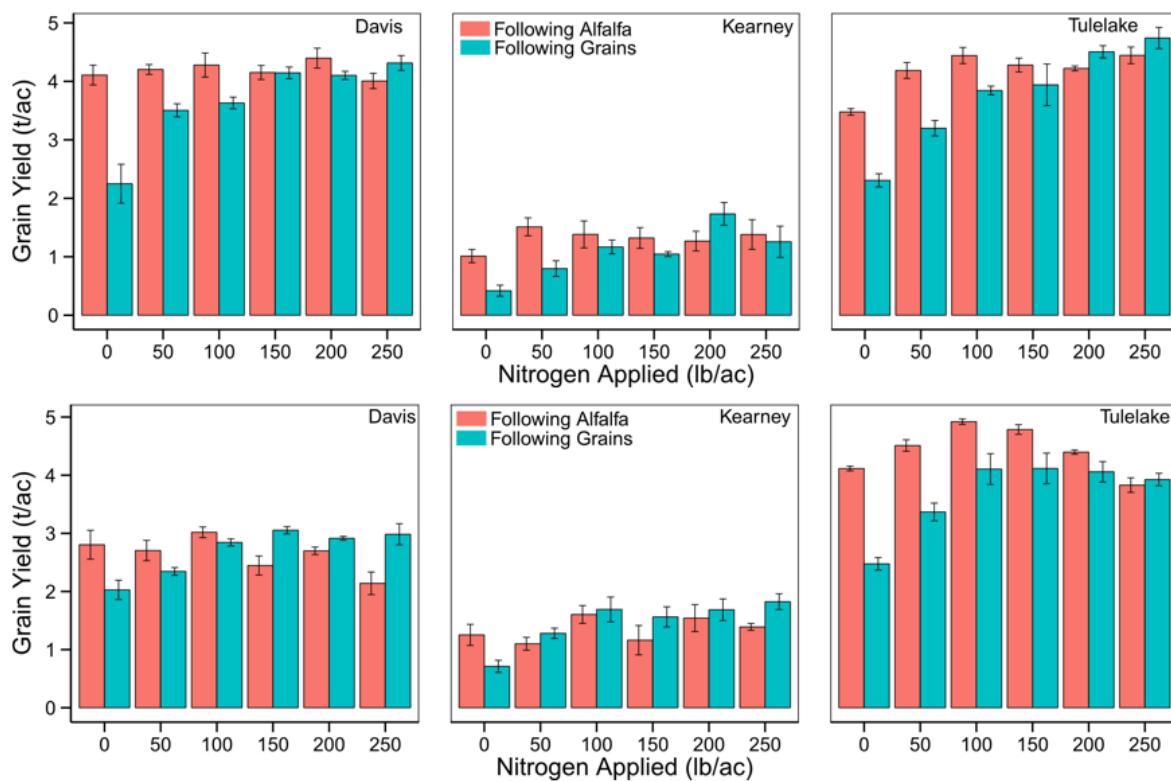


Figure 4. Grain yield for wheat fertilized with nitrogen rates ranging from 0 to 280 kg N ha⁻¹ in the ‘Following Alfalfa’ and ‘Following Grains’ treatments at Davis, Kearney, and Tulelake. Top: Results from 2013–2014 experiment. Bottom: Results from 2014–2015 experiment. Error bars indicate standard errors of the mean. Red bars indicate wheat grown after the ‘Following Alfalfa’ treatment. Blue bars indicate wheat grown after the ‘Following Grains’ treatment.

Grain yields between Davis and Tulelake had fairly similar ranges, despite differences in varieties used (Figure 4). At Kearney, grain yields ranged from 0 to 4.5 Mg ha⁻¹ and were comparatively much lower than grain yields at Davis and Tulelake, which ranged from 0 to 11.2 Mg ha⁻¹. Similar to total aboveground biomass, grain yield for wheat at Davis in the ‘Following Alfalfa’ treatment were not distinguishable between nitrogen fertilization treatments. This result was observed both years. In contrast, grain production from wheat in the ‘Following Grains’ treatment was distinguishable between different levels of N fertilization.

Grain Protein

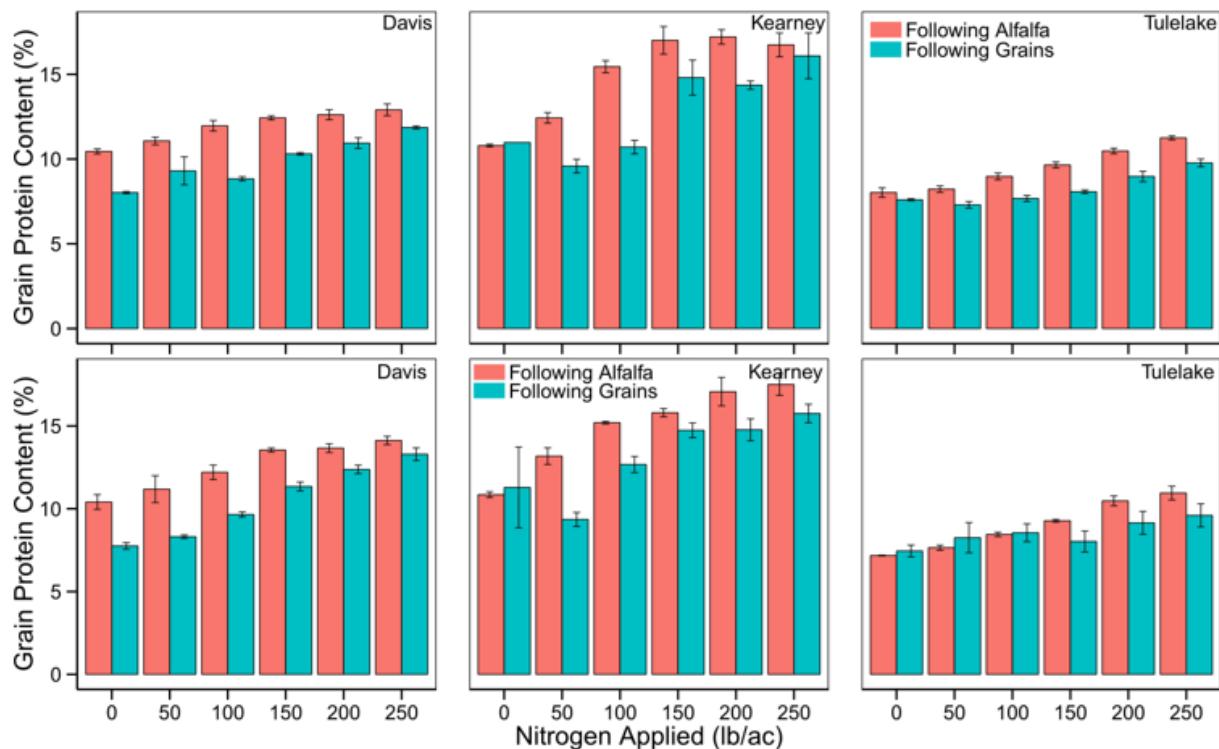


Figure 5. Grain protein for wheat fertilized with nitrogen rates ranging from 0 to 280 kg N ha⁻¹ in the ‘Following Alfalfa’ and ‘Following Grains’ treatments at Davis, Kearney, and Tulelake. Top: Results from 2013–2014 experiment. Bottom: Results from 2014–2015 experiment. Error bars indicate standard errors of the mean. Red bars indicate wheat grown after the ‘Following Alfalfa’ treatment. Blue bars indicate wheat grown after the ‘Following Grains’ treatment.

Grain Protein

For wheat grown at Tulelake from 2013–2014, there were distinguishable differences in grain protein between N rates along with distinguishable differences between rotation treatments ($p < 0.001$) – Figure 5. There was also a statistically significant interaction between the N rates and rotation treatments ($p < 0.05$). However, while there were also distinguishable differences in N rates ($p < 0.001$) and rotation treatments ($p < 0.05$) in wheat grown at Tulelake from 2014–2015, there was no interaction between the two treatments.

At Kearney, wheat grown in both the 2013–2014 and 2014–2015 experimental periods produced distinguishable differences in grain protein for the different N rates ($p < 0.001$) and rotation treatments ($p < 0.05$). There were also statistically significant interactions between the N rates and rotation treatments for both years ($p < 0.05$).

Davis wheat grown in 2014–2015 also had statistically significant interactions between N rate and rotation treatments ($p < 0.05$), as well as distinguishable differences between different N rates ($p < 0.001$) and rotation treatments ($p < 0.01$). For wheat in 2013–2014, distinguishable differences between different N rates ($p < 0.001$) were observed for both rotation treatments despite the lack of a response to N fertilization observed for above-ground biomass.

G. Discussion/Conclusions

Soil Nitrogen

While there were no distinguishable differences between the soil following grains and soil following alfalfa in total soil N, as measured in 2013, the Nitrate-N results from 2014 were as expected: the soil following alfalfa had a greater soil NO_3^- content than the soil following grains (Figure 3), ranging between 10 to 15 ppm in the top 15 cm, and decreasing with depth. Total soil N also appeared to decrease with depth. Taken together, these results indicate there likely was not very much soil nitrate leaching before the experiment began. Nitrate leaching was also unlikely because soil nitrate content did not increase with depth. Additionally, while Kearney had the lowest soil total N in 2013 of the three sites, regardless of the preceding rotation treatment, its NO_3^- content for soil following alfalfa in 2014 was comparable to those of the same treatment at the other two sites.

Aboveground Biomass

Previous experiments have indicated that the nitrogen credit from alfalfa could often easily satisfy the nitrogen needs of a corn crop (Yost et al., 2014). Our results from Davis in both years of the experiment have indicated that this fully satisfying of the N needs can also occur in irrigated wheat grown in a semiarid environment grown after an irrigated alfalfa crop. Despite the different crop, climate, cutting schedule, and management techniques, which could all significantly affect the amount of nitrogen fixed and mineralized, similar results were observed.

Unlike at Davis, however, results from Tulelake and Kearney indicates that there was insufficient residual soil N from alfalfa to fully satisfy the N needs of the wheat crop, or that the timing of crop uptake and soil N mineralization differed from availability. Especially at Tulelake, where the climate compared to Davis is quite different during the growing season, and very little N mineralization can occur because of the relatively cold winters, timing of crop uptake and soil N mineralization could significantly affect the amount of N that a legume such as alfalfa can contribute to subsequent crops. It's noteworthy that at this site, benefits from alfalfa rotation occurred even at high N fertilizer rates. At Kearney, the sandy soil could mean more N was lost during flood irrigations, which could decrease N uptake and yields. Wheat yields were low there. Wheat at Kearney may have experienced high temperature stress due to the high temperatures typically experienced there during the growing season, potentially reducing yield potentials (Harding et al., 1990).

In all location-years, the lack of a difference between the maximum aboveground biomass observed in both the wheat following alfalfa and the wheat following grains indicates that there was unlikely to be a significant non-nitrogen rotation effect. While crop rotations can generally help break disease cycles and reduce yield variability, the non-nitrogen rotation benefit from rotating wheat with sudangrass may have been sufficiently similar to the non-nitrogen from rotating wheat with alfalfa to make any possible differences indistinguishable.

Nitrogen Uptake

Nitrogen uptake data in Davis wheat for both years of the experiment showed that the wheat crop following alfalfa continued to be able to assimilate N even though it had reached its maximum aboveground biomass. This result could mean that wheat there did not have all of its N needs fully satisfied, possibly due to timing of uptake and mineralization. Most of the N required by the wheat for biomass accumulation may have been taken up earlier than the N required for grain production, and mineralization might not have matched the level of N assimilation the wheat required for producing optimal grain protein concentrations.

At Tulelake, the nitrogen uptake data from both years showed an increasing amount of nitrogen assimilation up to 200 kg N ha⁻¹. This result was similar to the biomass accumulation observed. Similar results were obtained at Tulelake in 2014–2015. Unlike at Davis, the N uptake seemed to correlate well with the amount of biomass. Similarly, at Kearney, both years showed plateaus in uptake and biomass accumulation at similar levels of nitrogen fertilization, as expected.

Grain Protein Content

Grain protein content may give different information from nitrogen uptake and whole-plant aboveground biomass. The statistically significant interactions between the N rate treatments and rotation treatments observed in four of five location-years tested for interactions could indicate that there were non-nitrogen rotation effects at play. Another possibility is that grain protein content may have reached a maximum at lower N fertilization rates for wheat grown after alfalfa, yielding a saturation-like N rate response as opposed to a linear response that might be observed for wheat in the ‘Following Grains’ treatment. The significant interaction would then simply be an artifact of the difference between a saturation-like response and a linear response observed in the two treatments.

Overall Conclusions:

Overall, unfertilized wheat following alfalfa produced more biomass, produced more grain, and took up more nitrogen than unfertilized wheat following the grains rotation (sudangrass/wheat). These results are in line with previous research on crop rotation, and suggest that the alfalfa was very likely to have contributed nitrogen that was

substantial enough to produce measurable differences in growth of the subsequent wheat crop compared to a control.

With several of the metrics used to evaluate wheat growth, unfertilized wheat following alfalfa performed about the same as wheat following sudangrass/wheat fertilized with 100 lb N ac⁻¹. Using this difference in wheat growth as a preliminary estimator of alfalfa's nitrogen credit, we estimate based on these first-year N uptake data that alfalfa contributed 114 lb N ac⁻¹, 82 lb N ac⁻¹, and 119 lb N ac⁻¹ at Davis, Kearney, and Tulelake, respectively (Figure 2).

H. Project Impacts.

Although much has been made of the necessity of doing a better job of managing N fertilizers in corn, wheat and other N-requiring crops, historically, the N credit for rotation with legumes has been largely ignored. This trial has been successful in identifying the N credits in non-legumes following alfalfa, and the first systematic experimentally-determined estimate developed for California, to our knowledge. Although quantitative results differed by soil type and location, we found N benefits to rotation at all locations in all years. A major challenge is to convince farmers, Crop Advisors and other decision-makers to make use of this consideration

If these credits are considered in adjusting recommendations for N fertilizer applications for wheat (or other non-legumes) following alfalfa, millions of tons of fertilizer applications could be saved in California. For example, if a modest 80 lbs N/acre credit (in the mid-range found in these trials) is provided to the crops following the estimated 150,000 acres of alfalfa rotated each year in the state, 12 million lbs. of actual N in applied fertilizer could be conserved, with a benefit to the farmer and the environment. A few caveats should be considered here when making recommendations on the N benefits of crop rotation with alfalfa. These trials were conducted under controlled conditions, with good stands of alfalfa plowed under and compared with grain-grain cropping systems. On farms, the status of alfalfa fields varies widely in plant density and weed intrusion by the time the fields are plowed under for rotation. Additionally, soil types vary widely in the ability to conserve residual N. The time elapsing between the vigorous growth of an alfalfa field and the subsequent crop may also vary widely, and these trials were planted shortly after crop plow-down. Therefore adjustments to estimated N benefits must be made based upon a range of circumstances and modified accordingly.

The benefits of crop rotation with a vigorous legume like alfalfa are clear from this research. Especially interesting is the impact of (Presumably) more slowly-available N during the later grain-filling period of wheat which had an impact on grain protein quality in many of the sites. Crop rotations with other legumes (such as cowpea, fieldbean and cover crops such as vetch) are less common, but also provide legume benefits to subsequent crops. At the very least, with wheat, this research indicates that growers should likely avoid prophylactic N applications at planting when following alfalfa, and instead monitor crop N status and apply N judiciously mid-season.

However, this research has quantified the N benefits to a subsequent grain crops and has implications for N recommendations of non-legumes. Crop rotations with alfalfa occur frequently in California, and can have major environmental benefits to the state's management of nitrogen.

I. Outreach Activities Summary.

Field Days and meetings were held to discuss results with growers at multiple times during this period.

- **May 15, 2013 Alfalfa/Forage Field Day, Davis. (90 participants)**
- **August 1, 2013 Tulelake Field Day (130 participants)3,**
- **September 5, 2013 Kearney Field Day (110 participants)**
- **September 30, 2013 FREP Conference, Modesto(200 participants)**
- **April 17, 2014 Imperial Valley Field Day, El Centro (90 participants)**
- **May 7, 2014 Davis Field Day, Davis (110 participants)**
- **August 13, 2014. Tulelake Field Day (100 participants).**
- **September 12, 2014 Kearney Field Day (120 participants)**
- **October 30, 2014 FREP Conference, Modesto, CA (200 participants)**
- **ASA meetings, Long Beach CA Poster (4,000 attending)**
- **December 5, 2015. California Alfalfa & Grains Symposium, Long Beach, CA (550 participants)**
- **April 15, 2015 Imperial Field Day, El Centro (110 participants)**
- **May 12, 2015 Davis Field Day, Davis, (95 participants)**
- **August 1, 2015 Field Day, Modesto (25 participants)**
- **September 18, 2015 Field Day, Kearney (120 participants)**
- **December 3, 2015 Western Alfalfa Symposium, Reno, 550 participants.**

At each of these events, a proceedings paper or a handout was prepared (see sample handout below).

For the CA Alfalfa Symposium, a video of the presentation can be seen at:
<http://alfalfa.ucdavis.edu/+symposium/2014/index.aspx>

At the 2015 Western Alfalfa Symposium in Reno a presentation was made:

<http://alfalfa.ucdavis.edu/+symposium/2015/PDFfiles/Lin%20Eric.pdf>

Powerpoints:

http://alfalfa.ucdavis.edu/+symposium/2015/powerpoints/22_LinAlfalfa&Nitrogen.pdf

J. Factsheet.

1. **Project Title:** Characterizing N Fertilizer Requirements of Crops Following Alfalfa
2. **Grant Agreement Number** (Assigned by CDFA): 12-0385-SA
3. **Project Leaders** (Include names and affiliations) Dan Putnam, Cooperative Extension Forage Specialist, Department of Plant Sciences, University of California, Davis, One Shields Ave. (530) 752-8982 dhputnam@ucdavis.edu; Stu Pettygrove (now retired), CE Soils Specialist, Department of Land, Air and Water Resources, University of California, Davis, One Shields Ave. (530) 752-2533 gspettygrove@ucdavis.edu; Eric Linn (graduate student, UC Davis). erlin@ucdavis.edu
4. **Start Year/End Year:** 2013-2015
5. **Locations:** Parlier, CA, Davis, CA, Tulelake, CA
6. **Counties:** Fresno County, Yolo County, Siskiyou County
7. **Highlights:**
 - Wheat planted in rotation with alfalfa produces higher yields than when rotated with grains at zero N applications, but even in most cases at higher N fertilizer rates. At some sites in some years, the complete N needs of wheat were satisfied by the rotational N contribution from alfalfa.
 - Wheat benefits from the residual N provided at no cost to the farmer— an N credit to wheat ranging from 70 to 130 lb. N/acre. We recommend that growers take this credit into account and apply fertilizer later in the growing season as the amount of this credit becomes apparent.
 - Grain protein of wheat was often benefitted by crop rotation with alfalfa, sometimes even at very high N fertilizer rates, indicating the value of residual organic N made available late in the growing season to the wheat crop.
8. **Introduction.** While many growers utilize the ‘recipe’ approach to fertilizer applications, there are both economic and environmental incentives to more carefully calculate requirements under different soil and crop rotation conditions, especially for mineral N. An important strategy is to better manage the N available from rotation from N-fixing crops such as alfalfa, which provide some

quantity of N to subsequent crops. Alfalfa in California is commonly rotated with wheat, corn, oats, processing tomato, cotton, and sometimes specialty vegetables; a minimum of 200,000 acres are likely rotated from alfalfa each year in California. Alfalfa is typically in place from 3 to 6 years, and almost always followed by a non-legume. Under irrigation, a productive alfalfa crop fixes between 350 and nearly 1,000 lbs of N per acre per year in California, totaling ~ 2,000 to 4,000 lbs N/acre over a 5 year alfalfa stand. While most of this N is likely removed in the forage, some quantity of residual nitrogen remains in the soil, a portion of which may be available to subsequent crops. This is due to the stable soil rhizosphere (without tillage), the sloughing off of root and nodule pieces, high quantities of soil microorganisms in a stable leguminous perennial system, the root mass itself, and the deposition of high-N containing foliage to the soil. On a statewide basis, if a modest N savings from crop rotations of 40 lbs N per acre over 200,000 acres were realized, this amounts to a potential fertilizer savings of 8 million lbs of N statewide each year, and a cost savings to California growers of \$3.2 million/year (based upon a \$0.40/lb of N price). This research was undertaken to measure the impact of the residual N available to the subsequent non-legume crop.

9. **Methods/Management.** Our approach to this was to establish comparative cropping systems at three sites in California which represent several of the major alfalfa growing regions in the state. This compared a grain-grain rotation (of approximately 1.5 to two years without N fertilization), with an alfalfa-grain rotation (of greater than 3 years in alfalfa). After these cropping systems were established (beginning before funding was available), we plowed-down the two systems and planted wheat over the entire area, and 6 levels of N fertilization were applied as a 'bioassay' of the value of the residual N available to a subsequent wheat crop. Both forage yields and grain yields were obtained and N analysis of plant tissue and grain was conducted. Differences between +alfalfa and -alfalfa in rotation was determined to be the N credit value of the crop rotation.
10. **Findings.** This multi-year trial was successful in identifying the N credits in non-legumes following alfalfa, and the first systematic experimentally-determined estimate developed for California, to our knowledge. Although quantitative results differed by soil type and location, we found N benefits to wheat rotated with alfalfa at all locations in all years. Comparing the amount of N uptake for wheat following alfalfa fertilized with 0 kg N ha⁻¹ and that for wheat following grains fertilized with 0 kg N ha⁻¹, the nitrogen credit at Davis was approximately 125 kg N ha⁻¹, 145 kg N ha⁻¹ at Tulelake, and 80 kg N ha⁻¹ at Kearney (112 lb. N/a, 129 lb N/a, and 71 lb N/a, respectively). These nitrogen credit estimates are relatively similar to estimates from other irrigated climates and cropping systems with similar growing conditions. These amounts should be adjusted based upon the status of the alfalfa field – for example whether the stand was adequate (plants per square foot), and whether foliage was vigorously growing when plowed down, the degree of weed intrusion, and soil-type considerations. The time elapsing between plow-down and wheat planting must be considered,

since some of this N may be lost during crop rotation. However, adjustments should be made to nitrogen recommendations for non-legume crops based upon these rotational considerations. If these credits are considered in adjusting recommendations for N fertilizer applications for wheat (or other non-legumes) following alfalfa, millions of tons of fertilizer applications could be saved in California. For example, if a modest 80 lbs N/acre credit (in the mid-range found in these trials) is provided to the crops following the estimated 150,000 acres of alfalfa rotated each year in the state, 12 million lbs. of actual N in applied fertilizer could be conserved, with a benefit to the farmer and the environment. The benefits of crop rotation with a vigorous legume like alfalfa are clear from this research. Especially interesting is the impact of (Presumably) more slowly-available N during the later grain-filling period of wheat which had an impact on grain protein quality in many of the sites. Crop rotations with alfalfa occur frequently in California, and can have major environmental benefits to the state's management of nitrogen.

Appendix A. Sample Handout from the Kearney Field Day, 2014

UC Research and Extension Center - Kearney Field Day, September, 2014

Characterizing N Fertilizer Requirements of Wheat Following Alfalfa

Dan Putnam, Stu Pettygrove, Steve Orloff, Rob Wilson, Shannon Mueller and Eric Lin¹
For more alfalfa information, see: <http://alfalfa.ucdavis.edu>

Description: This study began in 2012, and is being conducted at three locations in California (Tulelake, Davis, and Fresno County), funded by the Fertilizer Research and Education Program (CDFA-FREP). The first data will be collected in early 2014. Since N fertilizers are a major cost of production for wheat, corn and other crops, it's very important to accurately match the needs of the crop with fertilizer applications. It is well known that perennial legumes such as alfalfa contribute substantial quantities of residual soil N from N₂ fixation that can be absorbed by the following crop. Alfalfa can produce between 250 and almost 1,000 lbs. of N per acre per year (above ground, see Table 1), often greater than 90% originating from the atmosphere through N₂ fixation. The actual amount depends upon yield and protein concentration (Table 1). Although most of this N is removed in the crop, some portion remains to benefit the following crop.

Table 1. Crop removal of Nitrogen at different alfalfa yield and protein levels. Shaded area indicates most likely range for California Central Valley locations.

	Crude Protein of Alfalfa Forage					
	16	18	20	22	24	26
Tonnage (t/a)	%Nitrogen in Forage					
	2.56%	2.88%	3.20%	3.52%	3.84%	4.16%
Crop Removal of N						
lbs N/acre						
5	256	288	320	352	384	416
6	307	346	384	422	461	499
7	358	403	448	493	538	582
8	410	461	512	563	614	666
9	461	518	576	634	691	749
10	512	576	640	704	768	832
11	563	634	704	774	845	915
12	614	691	768	845	922	998

Shaded area represents most likely outcome

Objectives: Our objective is to determine the impacts of rotation with alfalfa on the N fertilization needs of the following wheat crop, to develop an 'N credit' recommendation for management of N fertilizers in non-legumes rotated with alfalfa.

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Methods: In this experiment, we have removed portions of an existing vigorous alfalfa field, and established wheat-sudangrass as a rotation at least 1 year in advance, with the objectives of removing any of the residual N. In the fall, we plow up both the alfalfa and the grains and establish wheat again. N fertilizers are applied at different rates to the wheat crop, and yield and quality response to N measured. Thus we have wheat following grains and wheat following alfalfa as treatments, along with N rates to estimate the N credit. Soil samples will characterize N profile prior to planting the test wheat crop. The ‘difference method’ will be used to estimate N credits ascribed to the legume (see graph)—this includes non-N rotation benefits (such as soil tilth, diseases, or other benefits) which may be present. This study will enable farmers to use N fertilizers more efficient and save money on N fertilizers, and to reduce the possible effects unnecessary N applications on groundwater quality.

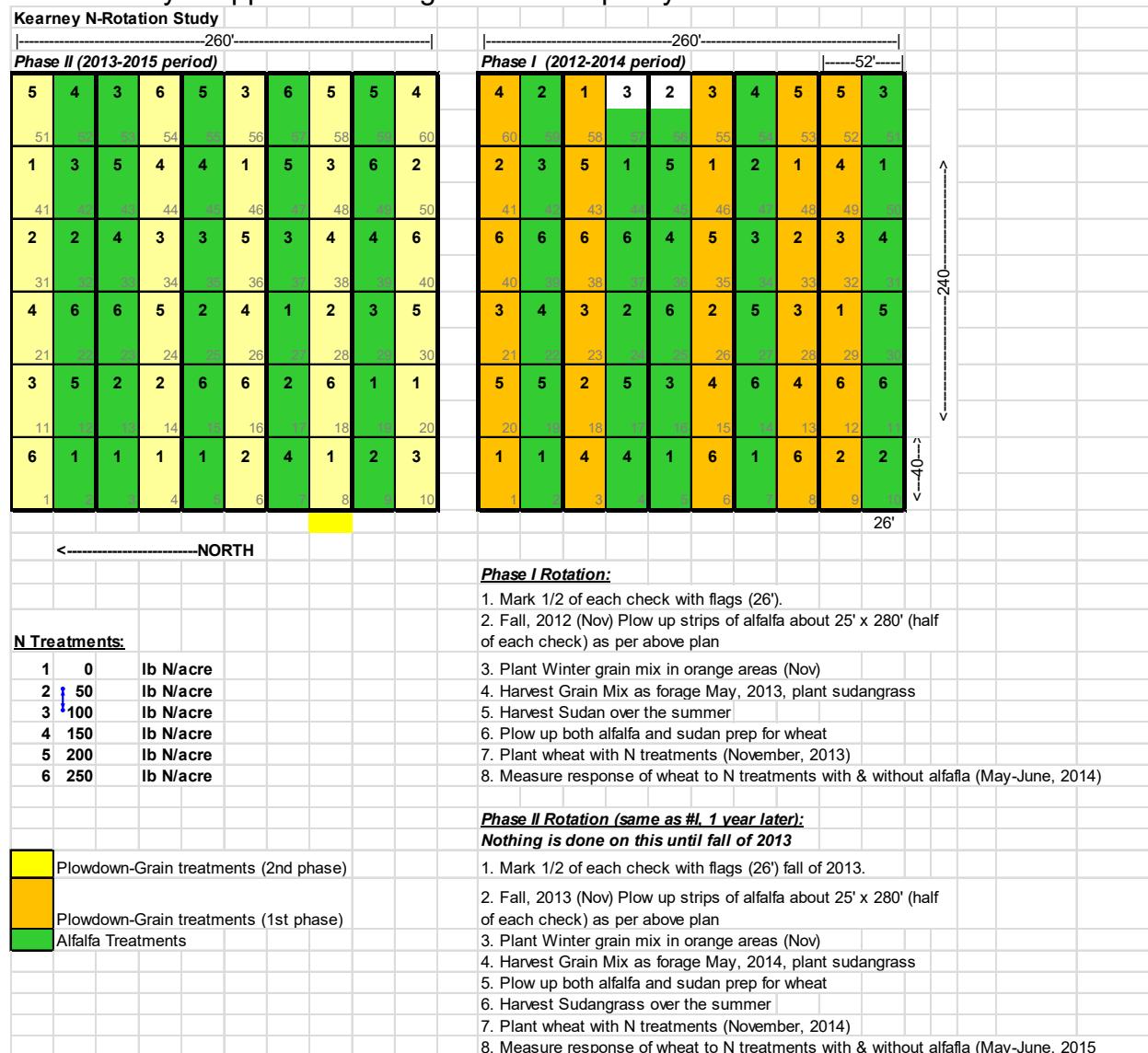
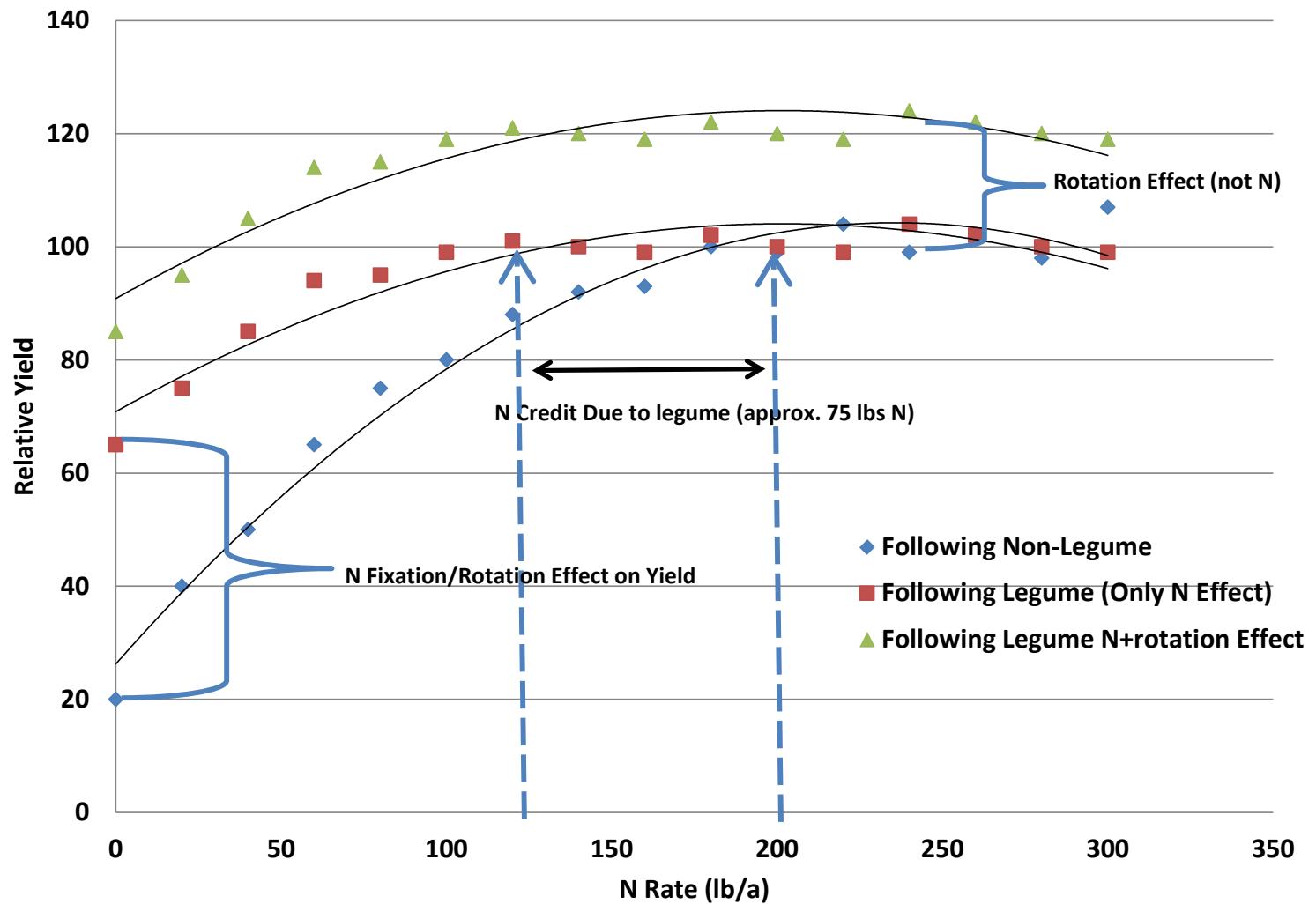


Table 1. Crop Sequence for the alfalfa-wheat rotation studies.

Phases	Year 1 (2012)	Year 1 (2013)	Year 2 (2014)	Year 3 (2015)
Tulelake Phase 1	Establish sudan strips	Continue Rotation Strips - Fall Wheat Establishment	Measure N response in wheat	
Tulelake Phase 2	Continuous alfalfa	Establish non-legume rotation	Continue Rotation Strips - Fall Wheat Establishment	Measure N Response in wheat
Davis Phase 1	Establish Sudan strips	Continue Rotation Strips - Fall Wheat Establishment	Measure N response in wheat	
Davis Phase 2	Continuous alfalfa	Establish non-legume rotation	Continue Rotation Strips - Fall Wheat Establishment	Measure N Response in wheat
Kearney Phase 1	Establish sudan strips	Continue Rotation Strips - Fall Wheat Establishment	Measure N response	

Hypothetical Data from Rotation N Responses in Wheat



Appendix B: Plot Plans

